

New physics search via Z' resonance

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SUSY 2009

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: various leptonic ($\ell = e, \mu$) resonances at LHC

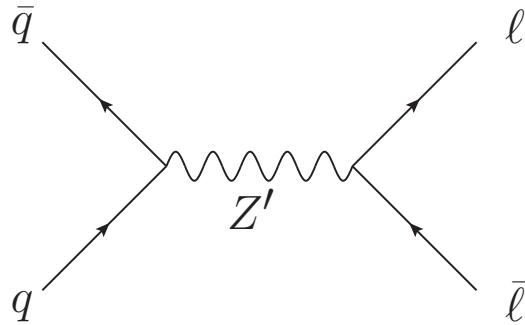
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Prelude

- 2 lepton resonance ($q\bar{q} \rightarrow Z' \rightarrow 2\ell$) : Z' search



Leptonic ($\ell = e, \mu$) resonance: clean signal even at hadron colliders.

Once Z' is discovered, the Z' may give other leptonic resonance such as

- 4 lepton resonance ($q\bar{q} \rightarrow Z' \rightarrow \dots \rightarrow 4\ell$) : SUSY search
- 6 lepton resonance ($q\bar{q} \rightarrow Z' \rightarrow \dots \rightarrow 6\ell$) : Higgs search

We explore the possibility after reviewing a relevant physics scenario.

Brief review of physics scenario

SUSY needs a companion symmetry

Quantum correction of Higgs mass ($\delta m_H^2 \sim \Lambda^2$) motivates SUSY.

Mere supersymmetrization of the SM has issues:

1. **Proton stability:**

\mathcal{L}, \mathcal{B} violating terms ($\lambda L L E^c, \lambda' L Q D^c, \lambda'' U^c D^c D^c, \dots$)

2. **DM candidate stability:**

LSP decays through \mathcal{L}, \mathcal{B} violating terms.

3. **μ -problem (Kim, Nilles [1984]):**

$W = \mu H_d H_u$ with $\mu \sim \mathcal{O}(\text{EW})$ is required in EWSB.

→ **SUSY needs a companion symmetry.**

SUSY companion symmetries

- R -parity : forbids renormalizable \mathcal{L} , \mathcal{B} violating terms.
- TeV scale $U(1)'$: replaces $\mu H_d H_u$ with $S H_d H_u$ ($\langle S \rangle \sim \text{EW/TeV}$).
($z[H_d] + z[H_u] \neq 0$, $z[S] + z[H_d] + z[H_u] = 0$)
(See P. Langacker's talk for general $U(1)'$ review.)

Various supersymmetric models:

R -parity only, R -parity + $U(1)'$, $U(1)'$ w/ R -parity inside, \dots

R -parity violating scenario

Consider a model with TeV scale $U(1)'$ and *manifest* R -parity violation.

$$U(1)' \rightarrow B_3 \times U_2$$

(Hur, HL, Luhn, Matchev, Nasri, Wang [2007 ~ 2008])

1. **Proton stability:** B_3 (Baryon triality)

(\mathcal{L} violating terms ($\lambda L L E^c$, $\lambda' L Q D^c$) are allowed, yet

$\Delta \mathcal{B} = 3 \times \text{integer} \rightarrow$ proton decay ($\Delta \mathcal{B} = 1$) never happens.)

2. **DM candidate stability:** U_2 (U -parity)

(Lightest hidden sector particle (LUP) is stable; it satisfies WMAP & CDMS/XENON constraints.)

3. **μ -problem:** $U(1)'$

\rightarrow **R -parity violating $U(1)'$ SUSY model is a viable scenario.**

How to test the model at LHC

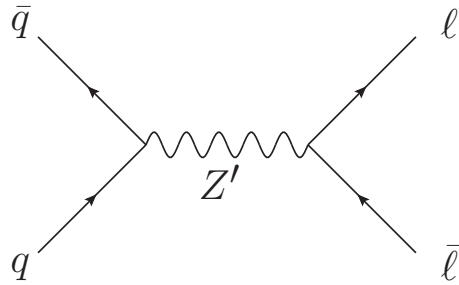
1. TeV scale $U(1)' \rightarrow Z'$ search
2. R -parity violation
3. Higgs doublets charged under $U(1)'$
- \vdots

How to test the model at LHC

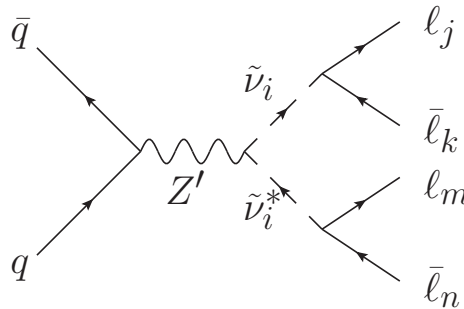
1. TeV scale $U(1)' \rightarrow Z'$ search
2. R -parity violation \rightarrow SUSY search
3. Higgs doublets charged under $U(1)' \rightarrow$ Higgs search
- \vdots

Among various channels, we want to consider possibility of pure leptonic resonance signals at LHC.

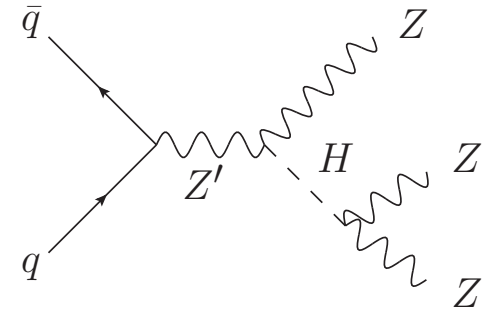
[Z' search (2ℓ)]



[SUSY search (4ℓ)]



[Higgs search (6ℓ)]



In this talk, we require only 10 events at resonance after appropriate cuts.
(Irreducible BKG for leptonic resonance with high invariant mass is small.)

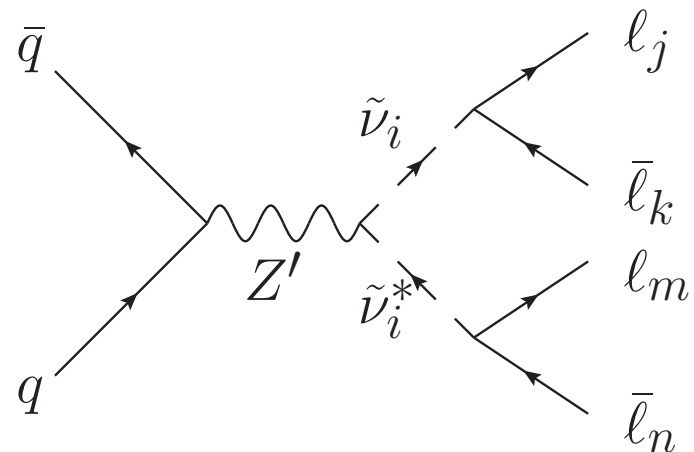
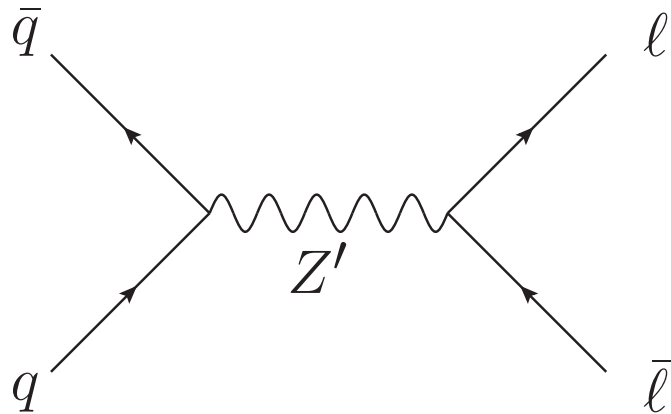
4 lepton resonance (SUSY search via Z')

: requires R -parity violation and $\tilde{\nu}$ LSP

HL [2008]

Connection of $U(1)'$ and R -parity violation at LHC

- **TeV scale $U(1)'$: Z' resonance** in dilepton channel
(ex: $q\bar{q} \rightarrow Z' \rightarrow e^+e^-$)
- **\mathcal{L} violation**: Z' produces LSP pair, and the **LSP decays into SM particles** through \mathcal{L} violating interaction
(ex: $q\bar{q} \rightarrow Z' \rightarrow \tilde{\nu}\tilde{\nu}^* \rightarrow 4 \text{ fermions (through } \lambda LLE^c, \lambda' LQD^c))$)



4 lepton resonance estimation (for $\tilde{\nu}_L$ LSP)

$$\begin{cases} \Gamma(Z' \rightarrow e^+e^-) = \frac{g_{Z'}^2}{24\pi} (z[e_L]^2 + z[e_R]^2) M_{Z'} \\ \Gamma(Z' \rightarrow \tilde{\nu}_L \tilde{\nu}_L^*) = \frac{g_{Z'}^2}{48\pi} z[e_L]^2 M_{Z'} \left(1 - \frac{4m_{\tilde{\nu}}^2}{M_{Z'}^2}\right)^{3/2} \end{cases}$$

$\lambda L L E^c$ (R -parity violating term)

$$\rightarrow 2z[e_L] - z[e_R] = 0$$

$$\rightarrow \Gamma(Z' \rightarrow \tilde{\nu}_L \tilde{\nu}_L^*) \sim 0.1 \times \Gamma(Z' \rightarrow e^+e^-) \quad \text{for } m_{\tilde{\nu}} \ll M_{Z'}.$$

$$\begin{aligned} \sigma_{4\ell} &\simeq \sigma(pp \rightarrow Z') \text{Br}(Z' \rightarrow \tilde{\nu} \tilde{\nu}^*) \text{Br}(\tilde{\nu} \rightarrow 2\ell)^2 \\ &\sim (0.1 \times \sigma_{e^+e^-}) \times \underbrace{\text{Br}(\tilde{\nu} \rightarrow 2\ell)^2}_{\text{4 light leptons from } \tilde{\nu} \text{ LSP pair}} \end{aligned}$$

4 light leptons from $\tilde{\nu}$ LSP pair

$\text{Br}(4\ell) \equiv \text{Br}(\tilde{\nu} \rightarrow 2\ell)^2$ depends on λ_{ijk} , λ'_{ijk} texture and $\tilde{\nu}$ LSP flavor.

$$(\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c)$$

We take $\text{Br}(4\ell)$ as an input parameter.

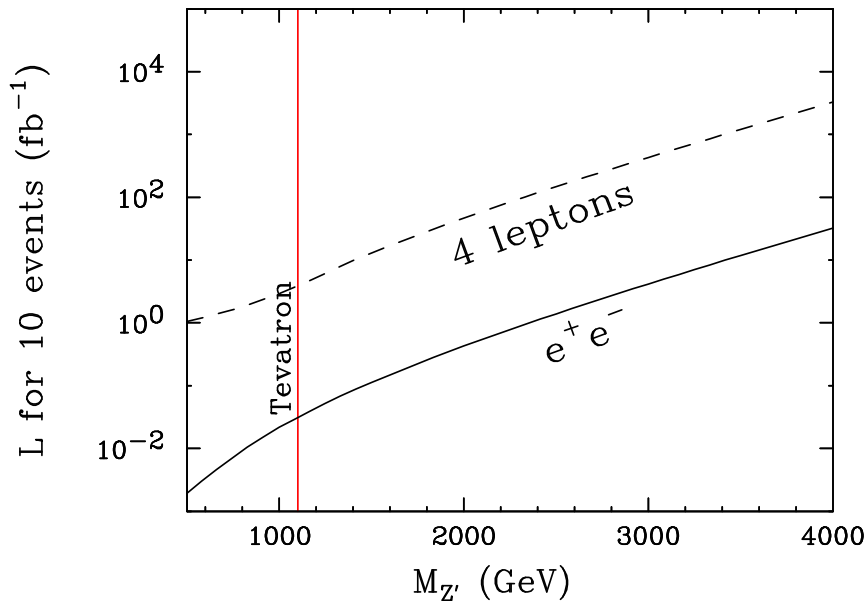
(ex) Light lepton production ratio for $|\lambda_{ijk}| = \text{constant} \gg |\lambda'_{ijk}|$

LSP pair	$eeee$	$eeee\mu$	$ee\mu\mu$	$e\mu\mu\mu$	$\mu\mu\mu\mu$	$\text{Br}(4\ell)$
$\tilde{\nu}_e \tilde{\nu}_e^*$	0	0	1	2	1	4/36
$\tilde{\nu}_\mu \tilde{\nu}_\mu^*$	1	2	1	0	0	4/36
$\tilde{\nu}_\tau \tilde{\nu}_\tau^*$	1	4	6	4	1	16/36

(For $m_{\tilde{\nu}} \sim \text{a few} \times 100 \text{ GeV}$, universal $|\lambda| \sim \mathcal{O}(10^{-3})$ is allowed by the LFV constraint.)

$\text{Br}(4\ell) \sim 0.1$ is realistic ($\sigma_{4\ell} \sim 10^{-2} \times \sigma_{e^+e^-}$).

Luminosity for 10 events for a chosen Z' coupling (respecting B_3)



$$\text{Br}(4\ell) = 0.1$$

$$m_{\tilde{\nu}} = 200 \text{ GeV}$$

$$\Gamma_{Z'} = 0.05 M_{Z'}$$

$$p_T > 20 \text{ GeV} \quad (\text{each lepton})$$

$$|\eta| < 2.4 \quad (\text{each lepton})$$

$$|m_{\text{inv}} - M_{Z'}| < 3 \Gamma_{Z'}$$

For $M_{Z'} = 1500 \text{ GeV}$, the required luminosity for 10 events at LHC:

- e^+e^- resonance : $L = 0.11 \text{ fb}^{-1}$ (Z' search)
- 4 lepton resonance : $L = 13 \text{ fb}^{-1}$ (SUSY search)

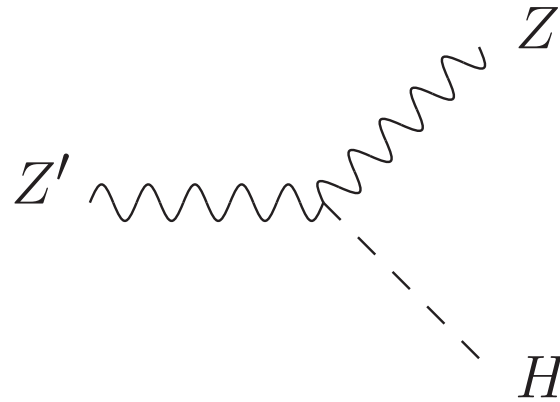
6 lepton resonance (Higgs search via Z')

: requires Higgs charged under $U(1)'$
(does not require SUSY)

[in progress]

Sizable Z' - Z - H coupling

$Z' \rightarrow ZH$: Studied in E_6 context by **Gunion, Haber, Roszkowski** in 1987, but has not been as a popular channel as others.



Z' - Z - H coupling (single H case for illustration):

$$\begin{aligned}\mathcal{L}_{\text{kin}} &= |D_\mu \Phi|^2 = \left| \left(\partial_\mu - \frac{i}{2} g_Z Z_\mu + i g_{Z'} z[H] Z'_\mu \right) \frac{1}{\sqrt{2}} (H + v) \right|^2 \\ &= -g_Z g_{Z'} z[H] v H Z_\mu Z'^\mu + \dots\end{aligned}$$

In general, $\Gamma(Z' \rightarrow ZH)$ depends on details of Higgs structure.

We take m_H and $\text{Br}(Z' \rightarrow ZH)$ as input parameters.

(ex) Single H case for illustration:

$$\begin{cases} \Gamma(Z' \rightarrow e^+e^-) = \frac{g_{Z'}^2}{24\pi} (z[e_L]^2 + z[e_R]^2) M_{Z'} \\ \Gamma(Z' \rightarrow ZH) \approx \frac{g_{Z'}^2}{48\pi} z[H]^2 M_{Z'} \quad (\text{for } M_Z, m_H \ll M_{Z'}) \end{cases}$$

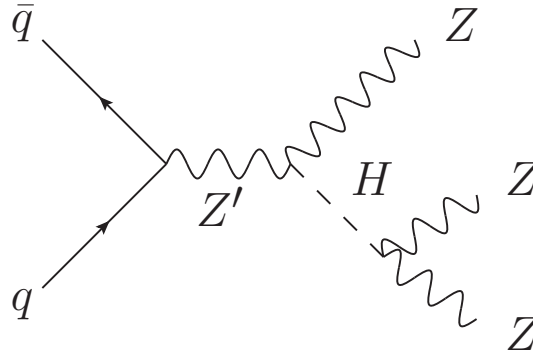
$$\Gamma(Z' \rightarrow ZH) \approx \Gamma(Z' \rightarrow e^+e^-) \quad \text{for}$$

$$z[e_R] = -z[e_L] = 0.5, z[H] = 1, m_H = 200 \text{ GeV}, M_{Z'} = 2 \text{ TeV}.$$

$\text{Br}(Z' \rightarrow ZH)$ can be as sizable as $\text{Br}(Z' \rightarrow e^+e^-)$.

6 lepton resonance estimation

We consider 6 light lepton ($\ell = e, \mu$) resonance with $m_H \gtrsim 2M_Z$.



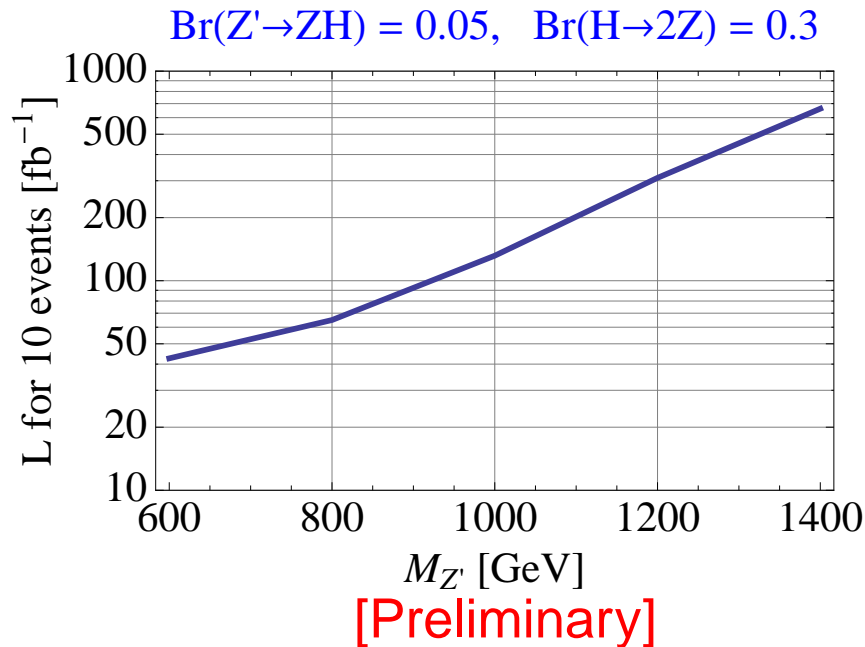
$$\begin{aligned}\sigma_{6\ell} &\simeq \sigma(pp \rightarrow Z') \text{Br}(Z' \rightarrow ZH) \text{Br}(H \rightarrow 2Z) \text{Br}(Z \rightarrow \ell\bar{\ell})^3 \\ &\sim \sigma(pp \rightarrow Z') \text{Br}(Z' \rightarrow ZH) \times 10^{-4}\end{aligned}$$

for $\text{Br}(H \rightarrow 2Z) \sim 0.3$.

$\sigma_{6\ell} \sim 10^{-4} \times [\text{typical } \mathcal{O}(\sigma_{e^+e^-})]$ is realistic.

Works even for leptophobic Z' (leptonic resonance for leptophobic Z').

Luminosity for 10 events for a chosen Z' coupling ($|g_{Z'} z[q_{L,R}]| = 0.5$)



$$m_H = 300 \text{ GeV}$$

$$\Gamma_{Z'} \simeq 0.1 M_{Z'}$$

$$p_T > 20 \text{ GeV} \quad (\text{each lepton})$$

$$|\eta| < 2.4 \quad (\text{each lepton})$$

$$|m_{\text{inv}}(\ell\bar{\ell}) - M_Z| < 3 \Gamma_Z \quad (3 \text{ pairs})$$

$$|m_{\text{inv}}(6\ell) - M_{Z'}| < 3 \Gamma_{Z'}$$

$M_{Z'}$ for 10 events of the 6ℓ resonance at LHC:

- $M_{Z'} = 920 \text{ GeV}$ for $L = 100 \text{ fb}^{-1}$ (1100 GeV for $L = 200 \text{ fb}^{-1}$)
- Can tell whether the Higgs doublet has $U(1)'$ charge if $M_{Z'}$ is not large.
- Combined w/ conventional channels, it can improve Higgs discovery potential. [Detailed analysis (including more channels) is in progress.]

Summary

1. Motivation order:

$$\text{Higgs} \rightarrow \text{SUSY} \rightarrow U(1)'$$

2. TeV scale $U(1)'$ is well motivated as a SUSY companion symmetry.

3. LHC implications (various leptonic resonances):

- 2ℓ resonance at $m_{2\ell} \sim M_{Z'}$: Z' search

- 4ℓ resonance at $m_{4\ell} \sim M_{Z'}$: SUSY search (for $\tilde{\nu}$ LSP)

$$\sigma_{4\ell} \sim (0.1 \times \sigma_{e^+e^-}) \times \text{Br}(4\ell) \Rightarrow 10^{-2} \times \sigma_{e^+e^-}, \text{ possibly}$$

- 6ℓ resonance at $m_{6\ell} \sim M_{Z'}$: Higgs search (for $m_H > 2M_Z$)

$$\sigma_{6\ell} \sim 10^{-4} \times \sigma_{pp \rightarrow ZH} \Rightarrow 10^{-4} \times \sigma_{e^+e^-}, \text{ possibly}$$

Allowing jets and MET can test more variety of scenarios:

(ex) Higgs with $m_H < 2M_Z$ ($2\ell + 2b$ -jet), other type LSP, etc.

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Allowing jets and MET can test more variety of scenarios:

(ex) Higgs with $m_H < 2M_Z$ ($2\ell + 2b$ -jet), other type LSP, etc.

$\rightarrow Z'$ is a great venue to search for other important new physics.